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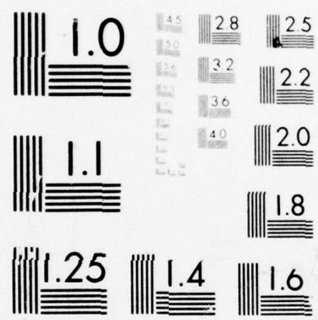

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THEORY OF SURFACE POLARITONS IN n-InSb IN THE PRESENCE OF A DC CURRENT AND AN EXTERNAL DC MAGNETIC FIELD*

B. G. Martin, A. A. Maradudin and R. F. Wallis

Department of Physics, University of California
Irvine, California 92717, USA

Abstract: The dispersion relation for p-polarized surface polaritons has been obtained for n-InSb when a dc electric current is flowing parallel to the surface. An external, dc magnetic field, parallel to the surface, and perpendicular to the direction of propagation of the surface polariton, is assumed to be present. The solutions of the dispersion relation show that the presence of the magnetic field shifts the surface polariton dispersion curve with respect to the no-field curve. The inclusion of damping leads to backbending of the dispersion curves across the light line. Amplification of the surface polariton can occur for drift velocities greater than a certain critical value.

INTRODUCTION

We have theoretically investigated surface polaritons in n-type InSb in the presence of drifting current carriers /1/.

Several theoretical investigations /1-5/ have been made of the possibility of observing instabilities, e.g. amplifying surface waves (not specifically surface polaritons), in a semiconductor due to drifting current carriers. The effect of an electric current on surface waves has also been observed experimentally /6,7/. In contrast to these investigations, where both electron and hole carriers were taken into account, our investigation is concerned only with drifting electrons. Although the surface polariton dispersion relations given here formally include a dc magnetic field, the calculations presented neglect its effect.

We consider a semiconductor which is infinite in the x- and y- directions and semi-infinite in the z-direction. It is assumed that the motion of an average carrier in the semiconductor is governed by the transport equation / 8 /,

$$[\dot{\vec{V}} + (\vec{V}\cdot\vec{\nabla})\vec{V}] = \frac{-\nabla P}{mN} + \frac{\delta}{m}[\vec{E} + \frac{1}{c}\vec{V}\times\vec{B}] - \nu\vec{V}, \tag{1}$$

where $\vec{V}$ and ν are the velocity and carrier collision frequency, respectively; $\vec{E}$ and $\vec{B}$ are the total electric and magnetic fields, respectively; and m and N are the mass and particle density, respectively; finally, ∇P is the electron thermal pressure gradient.

In what follows, we first consider the case in which the pressure gradient $\nabla P = 0$ and then consider the case that $\nabla P \neq 0$. In the first case, retardation is taken into account, while in the second case it is neglected (i.e. we assume the electrostatic limit).

SURFACE POLARITON DISPERSION RELATION (PRESSURE GRADIENT $\nabla P = 0$)

We linearize Eq. (1), taking $\nabla P = 0$, by writing $\vec{V} = \vec{V}_o + \vec{v}$, $\vec{B} = \vec{B}_o + \vec{b}$, and $\vec{E} = \vec{E}_o + \vec{e}$, where $\vec{V}_o$, $\vec{B}_o$, and $\vec{E}_o$ are uniform and time-independent quantities, while $\vec{v}$, $\vec{b}$, and $\vec{e}$ are position and time-dependent deviations from these uniform and static quantities. The linearized expressions are substituted into Eq. (1) and terms of like-order on both sides are equated, with only zero- and first-order terms being considered. In addition, an exponential variation $\exp[i(\vec{k}\cdot\vec{r} - \omega t)]$ is assumed for all first-order quantities. From the expression for the current density which is obtained in this way the non-local conductivity tensor $\sigma_{\alpha\beta}$ is obtained in a straightforward manner, and consequently we obtain the non-local dielectric tensor

$$\varepsilon_{\alpha\beta}(\vec{k},\omega) = \varepsilon_{\alpha\beta}(\omega) + \frac{4\pi i}{\omega}\sigma_{\alpha\beta}(\vec{k},\omega).$$

We next apply the so-called dielectric approximation / 9 / to $\varepsilon_{\alpha\beta}(\vec{k},\omega)$. Specifically, we must evaluate the partially transformed dielectric tensor which is defined as / 9 /

$$\epsilon_{\alpha\beta}(k\ \omega|zz') = \int_{-\infty}^{\infty} \frac{dk_z}{2\pi}\, \epsilon_{\alpha\beta}(\vec{k},\omega) e^{ik_z(z-z')}, \tag{2}$$

where $k^2 = k_x^2 + k_y^2$ (we will take $k_y = 0$ in the calculations).

To obtain the surface polariton dispersion relation for the geometry being considered here, taking retardation into account, we first obtain expressions for the fields $E_x(z)$ and $E_z(z)$ in the crystal $(z > 0)$ from the following coupled integro-differential equations.

$$\frac{-d^2}{dz^2} E_x(z) + ik_x \frac{d}{d_z} E_z(z) =$$

$$= \frac{\omega^2}{c^2}\int_0^{\infty} dz\ \epsilon_{xx}(k_x\omega|zz')E_x(z') +$$

$$+ \frac{\omega^2}{c^2}\int_0^{\infty} dz'\epsilon_{xz}(k_x\omega|zz')E_z(z') \tag{3}$$

$$ik_x \frac{d}{d_z} E_x(z) + k_x^2\, E_z(z) =$$

$$= \frac{\omega^2}{c^2}\int_0^{\infty} dz'\epsilon_{zx}(k_x\omega|zz')E_x(z') +$$

$$+ \frac{\omega^2}{c^2}\int_0^{\infty} dz'\epsilon_{zz}(k_x\omega|zz')E_z(z') \tag{4}$$

We next obtain the field component $D_z(z)$, and apply the boundary conditions of continuity of $E_x(z)$ and $D_z(z)$ at $z = 0$, the crystal-vacuum interface. The resultant surface polariton dispersion relation for a carrier drift velocity V_{ox} in the x-direction is

$$\frac{1}{\alpha_o} + \frac{ik_x(\alpha_4 + i\alpha\alpha_5) + \alpha(\epsilon_\infty - \alpha_6)}{k_x^2 - \frac{\omega^2}{c^2}(\epsilon_\infty - \alpha_6)} = 0\ , \tag{5}$$

where

$$\alpha_o^2 = k_x^2 - \frac{\omega^2}{c^2}$$

$$\alpha^2 = \frac{\left(k_x^2 - \epsilon_\infty \frac{\omega^2}{c^2}\right)\left(\epsilon_\infty - \frac{\alpha_2}{\alpha_1}\right) + \frac{\omega^2}{c^2}\alpha_6\left(\epsilon_\infty - \frac{\alpha_2}{\alpha_1}\right) - \frac{\omega^2}{c^2}\alpha_4^2}{-\frac{\alpha_3}{\alpha_1}\left(k_x^3 - \epsilon_\infty\frac{\omega^2}{c^2}\right) + \epsilon_\infty - \alpha_6 - 2k_x\alpha_5}$$

$$\alpha_1 = m^2\omega^2(\omega - k_xV_{ox})\left[(\omega - k_xV_{ox} + i\nu)^2 - \omega_c^2\right]$$

$$\alpha_2 = \epsilon_\infty m^2\omega^2\omega_p^2(\omega - k_xV_{ox} + i\nu)$$

$$\alpha_3 = \epsilon_\infty m^2\omega_p^2 V_{ox}(\omega - k_xV_{ox} + i\nu)$$

$$\alpha_4 = \frac{i\epsilon_\infty\omega_c\omega_p^2}{\omega\left[(\omega - k_xV_{ox} + i\nu)^2 - \omega_c^2\right]}$$

$$\alpha_5 = \frac{\epsilon_\infty\omega_p^2 V_{ox}(\omega - k_xV_{ox} + i\nu)}{\omega^2\left[(\omega - k_xV_{ox} + i\nu)^2 - \omega_c^2\right]}$$

$$\alpha_6 = \frac{\epsilon_\infty\omega_p^2(\omega - k_xV_{ox})(\omega - k_xV_{ox} + i\nu)}{\omega^2\left[(\omega - k_xV_{ox} + i\nu)^2 - \omega_c^2\right]}$$

and where we have introduced the plasma frequency ω_p, the cyclotron frequency ω_c, and ϵ_∞ is the background dielectric constant.

Figures 1 and 2 show results for two values of the drift velocity V_{ox}, where the collision frequency ν and the static magnetic field B_{oy} were taken to be zero.

SURFACE POLARITON DISPERSION RELATION (PRESSURE GRADIENT $\nabla P \neq 0$)

The procedure here parallels that used for the case where $\nabla P = 0$ except that, in the electrostatic limit, the coupled integro-differential equations (3) and (4) are placed by a single equation for the scalar potential $\phi(k_x\omega|z)$, namely,

$$ik_x\left\{-ik_x\int_0^{\infty} dz'\epsilon_{xx}(k_x\omega|zz')\phi(k_x\omega|z') -\right.$$

$$\left.-\int_0^{\infty} dz'\epsilon_{xz}(k_x\omega|zz')\frac{d}{dz'}\phi(k_x\omega|z')\right\} +$$

$$\cdot + \frac{d}{dz}\left\{-ik_x \int_0^\infty dz'\epsilon_{zx}(k_x\omega|zz')\phi(k_x\omega|z') - \right.$$

$$\left. - \int_0^\infty dz'\epsilon_{zz}(k_x\omega|zz')\frac{d}{dz'}\phi(k_x\omega|z')\right\} = 0 . \qquad (6)$$

From the solution of this equation the surface polariton dispersion relation for zero magnetic field is found to be

$$\frac{\epsilon_\infty\alpha_1 + k_x - \frac{\epsilon_\infty}{2}\frac{\omega_p^2}{\omega^2}B - \frac{\epsilon_\infty}{2}\frac{\omega_p^2}{\omega^2}\frac{3\omega}{V_F^2}\frac{\omega - k_xV_{ox}}{B+\alpha_1}}{\epsilon_\infty\alpha_2 + k_x - \frac{\epsilon_\infty}{2}\frac{\omega_p^2}{\omega^2}B - \frac{\epsilon_\infty}{2}\frac{\omega_p^2}{\omega^2}\frac{3\omega}{V_F^2}\frac{\omega - k_xV_{ox}}{B+\alpha_2}} -$$

$$- \frac{B + \frac{3}{V_F^2}\frac{\omega - k_xV_{ox}}{B-\alpha_1}}{B + \frac{3\omega}{V_F^2}\frac{\omega - k_xV_{ox}}{V-\alpha_2}} = 0 , \qquad (7)$$

where

$$B^2 = k_x^2 - \frac{3}{V_F^2}(\omega - k_xV_{ox})^2 > 0$$

$$\alpha_1^2 = \frac{1}{2}\left(a + \sqrt{a^2 - 4b}\right)$$

$$\alpha_2^2 = \frac{1}{2}\left(a - \sqrt{a^2 - 4b}\right) .$$

In these expressions, we have that

$$a = k_x^2\left(2 - \frac{3V_{ox}^2}{V_F^2}\right) + k_x\left(\frac{6\omega V_{ox}}{V_F^2}\right) -$$

$$- \frac{3\omega^2}{V_F^2}\left(1 - \frac{\omega_p^2}{\omega^2}\right)$$

$$b = k_x^2\frac{\omega_p^2}{\omega^2}\left[k_x\left(1 - \frac{3V_{ox}^2}{V_F^2}\right) + \frac{3V_{ox}\omega}{V_F^2}\right]^2 +$$

$$+ k_x^2B^2\left[1 - \frac{\omega_p^2}{\omega^2}\left(1 - \frac{3V_{ox}^2}{V_F^2}\right)\right]$$

$$V_F^2 = \frac{2}{m}\epsilon_F^o ,$$

where V_F is the fermi velocity and ϵ_F^o is the Fermi energy.

Figures 3 and 4 show the dispersion curves for the case where $\nabla P \neq 0$; for several values of drift velocity V_{ox}.

DISCUSSION

Fig. 1 shows the surface polariton dispersion curve for $V_{ox} = 7.29 \times 10^8$ am/sec. For $k_{1x} > 0$ ($k_x = k_{1x} + ik_{2x}$) there is a single branch, which increases with frequency. This branch is essentially mirrored for the case where $k_{1x} < 0$ except that this branch exhibits back bending. For $k_{1x} < 0$, however, there are two additional branches which move from large negative k_1-values toward the value $k_{1x} = 0$ as the frequency is increased. At some point to the left of the ω/ω_p axis, the two branches meet, and continue coincidentally, until they terminate at $k_{1x} \sim 0$. In this region of coincidence, the wave vectors are complex conjugate; thus, for one sign of the imaginary part of k_x, there appears to be amplification of surface polaritons, while for the other sign there is damping.

In Fig. 2, the surface polariton dispersion curves are shown for a drift velocity three orders of magnitude smaller than the one that has just been considered. The behavior is similar to that shown in Fig. 1.

Fig. 3 shows the dispersion curves for $V_{ox} = 0$, and $V_{ox} / V_F = 0.008$ ($V_F \sim 10^8$ cm/sec), but where the thermal pressure gradient is taken into account (see Eq. 7). There are branches for both $\pm V_F k_{1x}/\omega_p$, which increase rapidly with increasing frequency.

Fig. 4 shows results for $V_{ox}/V_F = 0.8$. There are, for this situation, only values of $+V_F k_{1x}/\omega_p$ that satisfy the dispersion relation. Initially, for increasing frequency, $V_F k_{1x}/\omega_p$ increases; then it bends back towards the frequency axis. Subsequently, for increasing ω/ω_p, the wave vector again increases. At the beginning of this increase, the wave vector values satisfying the dispersion relation are complex conjugate. Again we have an instability which is indicative of surface polariton amplification. The complex conjugate roots occur for values of $V_{ox}/V_F \gtrsim 0.5$.

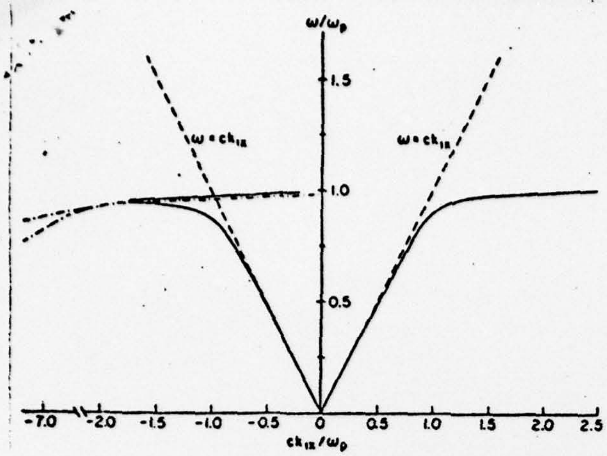

Fig. 1. Dispersion curves for surface polaritons with retardation and with carrier drift velocity V_{ox} = 7.29 x 10^8 cm/sec.

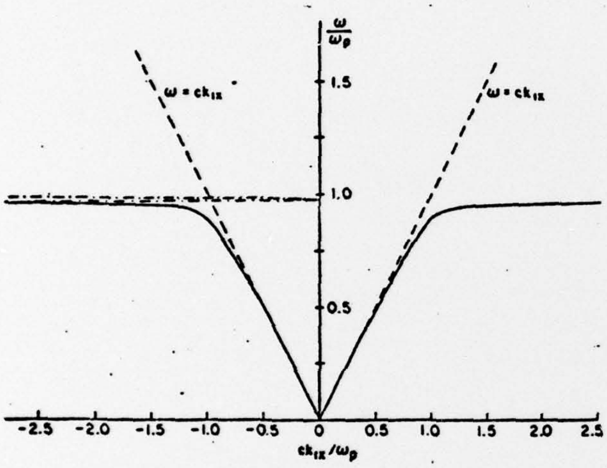

Fig. 2. Dispersion curves for surface polaritons with retardation and with carrier drift velocity V_{ox} = 7.29 x 10^5 cm/sec.

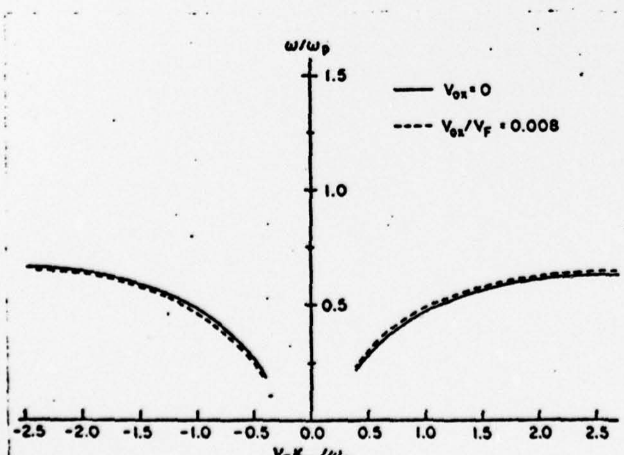

Fig. 3. Dispersion curves for surface polaritons without retardation but with the pressure gradient included.

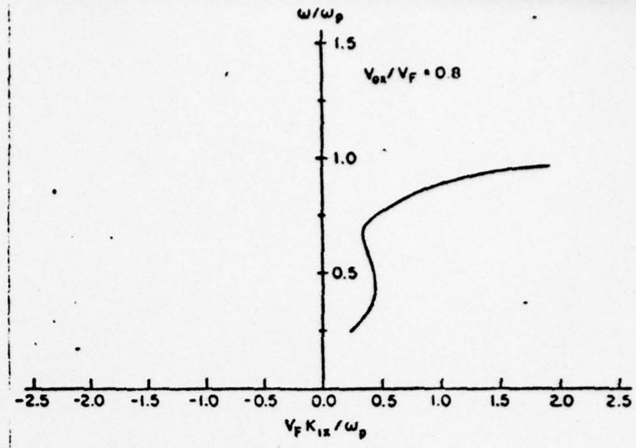

Fig. 4. Dispersion curves for surface polaritons without retardation but with the pressure gradient included.

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